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RESEARCH MEMORANDUM

CONTROLS FOR SUPERSONIC MISSILES

By George E. Kaattari, William A. Hill, Jr., and
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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

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INTRODUCTION

In recent years much work has been done to meet the requirements of missile control designers for more powerful controls and for lower hinge moments. One of the principal difficulties encountered in controlling missiles at high altitudes is the decrease with increases in altitude of the rate of change of flight path angle per unit control deflection (ref. 1). A type of control adapted to overcoming this difficulty is the all-movable wing by virtue of its large control area and its effectiveness at large control deflections. However, data on this type of control are meager for high Mach numbers and for extreme control deflections. To provide such data a special investigation was undertaken in the Ames 1- by 3-foot supersonic wind tunnel primarily for a Mach number of 3.36. The first part of this paper is concerned with the principal results of this investigation, particularly with the nonlinearities encountered in operating all-movable wings to extreme performance. It should be noted that these results are equally applicable to canard flippers used for trim and to all-movable horizontal- or vertical-tail surfaces.

ALL-MOVABLE WINGS

Effectiveness

The maximum panel lifts for a number of all-movable wings tested alone and in the presence of the body have been obtained from semispan tests. The wings are of biconvex section cut off so that the trailing-edge thickness is 2 percent and the maximum thickness is 4 percent. The body radius is one fifth of the combination semispan. Figure 1 shows on the left the lift coefficients for

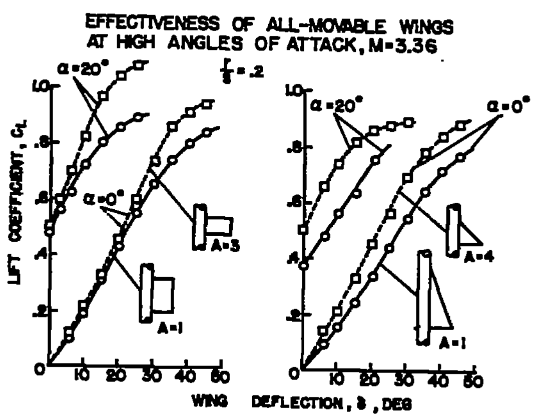

Figure 1

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two rectangular all-movable wings of differing aspect ratio and on the right the lift coefficient for two triangular all-movable wings. The lift is presented as a function of wing deflection for a body angle of attack of 0° and then for a body angle of attack of 20° for both sets of controls. For the zero angle-of-attack cases, the wing effectiveness does not decrease significantly until an angle of deflection of about 35° is reached. The effectiveness then decreases rapidly until maximum lift is reached near 45°. For a body angle of attack of 20°, the wings reach maximum lift near 25° deflection angle. It thus appears that the maximum lift of both rectangular and triangular controls is reached at a combined angle of the angles of attack and wing deflection of about 45°, at least for a Mach number of 3.36. This result is in accordance with previous results for wings alone (ref. 2) at other Mach numbers.

The manner in which the maximum panel lift varies with the various parameters is of interest from the standpoint of maximum maneuverability. Figure 1 shows that maximum maneuverability will be increased by changing from a triangular control to a rectangular control, but will be decreased by reducing the aspect ratio for either plan form. Wing-alone tests from Mach numbers of 1.5 to 3.36 also show these same results. Wing-alone tests show that the maximum lift coefficient decreases as the Mach number increases.

Hinge Moments

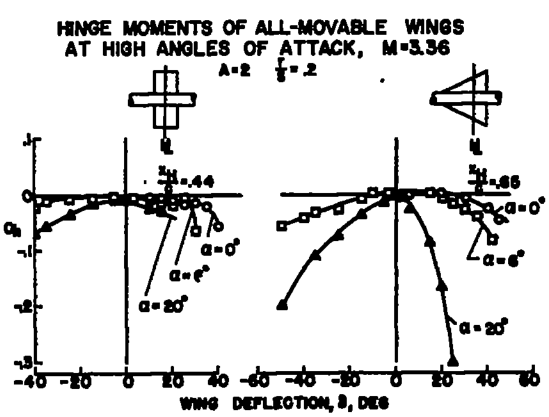

Figure 2

Figure 2 has been prepared to illustrate the types of nonlinearities in the hinge moments of all-movable controls. In this figure the hinge-moment coefficients are compared for two all-movable wings of triangular and rectangular plan form but of equal area, span, and aspect ratio. The reference area is taken to be the exposed panel area and is the same for the two wings. The reference length is taken to be the body diameter and is also the same for the two wings. Curves are presented for constant values of angle of attack of 0°, 6°, and 20°. Only the right half of the curve for 0° has been included because of symmetry. The hinge lines have been located to minimize the hinge moments for 0° angle of attack and small wing deflection. The curves are for deflections up to those for maximum lift obtainable. Nose-down hinge moments are negative.

It appears that the hinge moments are generally nonlinear because the controls are closely balanced. They are nonlinear in the sense that departures from straight lines are not negligible in terms of the maximum hinge moment. If the curves were linear for the zero angle-of-attack case, then the control could be more closely balanced by moving the hinge line; thus, maintaining linearity and keeping the hinge moments low are conflicting requirements.

The hinge-moment coefficients for the triangular wing become very large and negative at large angles of attack and wing deflection. In fact, they exceed those for the comparable rectangular control by an order of magnitude. This significant difference due to plan form has a simple explanation. When the all-movable control operates at large deflection angles, the loading in the wing-body juncture decreases because the body is a poor reflection plane under such conditions. Also at high body angles of attack, body upwash is lost in the juncture, further reducing the loading there. As a consequence the wing loading moves outboard approximately along the midchord line. For purely geometric reasons this outboard movement of the loading produces hinge moments for the triangular wing but not for the rectangular wing. It can be inferred from this reason for the nonlinear behavior of the triangular wing that the behavior will also occur at other Mach numbers. It should be realized that the large hinge moments of the triangular wing can be overcome in part by sweeping the hinge line. This cure requires some modification of the gap between wing and body to avoid physical interference when the wing is rotated.

The nonlinearities in hinge-moment coefficient can be explained in terms of changes in center-of-pressure position of the control. For the zero angle-of-attack case the centers of pressure for both the rectangular and triangular controls move rearward about 1 percent of the mean aerodynamic chord between 0° and 35° of deflection. With reference to figure 2 the difference in hinge moments for the rectangular wing between the cases of 0° and 20° angle of attack is associated with a movement of the center of pressure of 1 percent of the mean aerodynamic chord. The difference for the triangular wing is associated with a shift of the center of pressure of 8 percent of the M.A.C. in the case of the maximum difference in hinge moments.

Maneuverability at High Altitudes

The essential difference in the hinge-moment nonlinearities of rectangular and triangular controls at high angles of attack and control deflection is of importance at high altitudes. To show how important the difference can be, the torque of the servo necessary to actuate the control surface has been calculated as a function of the normal acceleration for a hypothetical antiaircraft missile at 65,000 feet. The hinge lines are located as in figure 2 to balance the control closely at 0° angle of attack and small wing deflections. This hinge-line location keeps the servo torque within reasonable limits when the missile is flying at high speeds at low altitudes. With this hinge-line location large servo torques can occur at high altitudes where maneuver loads act on the wing at relatively large distances from the hinge line.

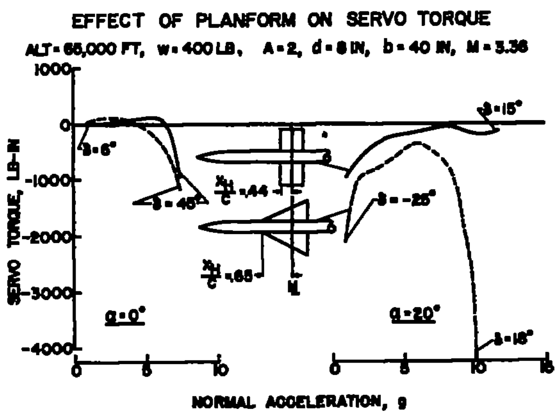

Figure 3

The servo torques required for maneuvering at high altitudes are shown in figure 3 for 0° and 20° body angle of attack. For a given missile with a fixed tail there exists a relationship between angle of attack and control deflection for trim, but in this example no tail has been included. For the zero angle-of-attack case there is no great difference between the servo torques of the two wings at the highest normal acceleration of about 7 g's. However, for an angle of attack of 20° and a normal acceleration of 10 g's the servo torque for the triangular wing is greater than that for the rectangular wing by an order of magnitude. This shows the importance at high altitude of hinge-moment nonlinearities. It is interesting to note that because of body lift, the rectangular control develops a maximum acceleration of 12 g's at an angle of attack of 20° compared to a value of 7 g's at 0° angle of attack.

Effect of Mach Number

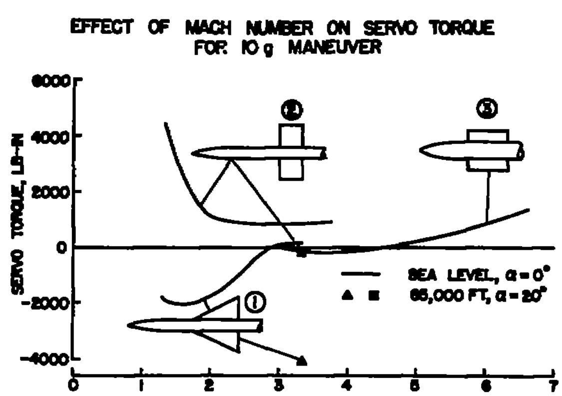

Figure 4

To show the nonlinear effects of Mach number on servo-torque requirements at low altitude, figure 4 is presented for a 10-g maneuver at sea level. Configurations 1 and 2 correspond to those of figure 3. Configuration 3 has been added to extend the Mach number range for rectangular controls into the hypersonic regime. This configuration has the same wing area as the other configurations but has an aspect ratio of unity based on the exposed wing panels joined together. Its ratio of body diameter to total span is twice that of the other configurations, and it is hinged at the

41-percent chord. For each configuration the hinge line is located to minimize the torque for a Mach number of 3.36 and small wing deflections. The curves of the figure are all for an angle of attack of 0°. For configurations 1 and 2 the trends of torque with Mach numbers have been calculated by adding a small correction for interference to the wing-alone data (ref. 3). For configuration 3 data were available from tests in the Ames 10- by 14-inch wind tunnel. Data for all-movable wings in the presence of the body also confirm the trend for configuration 1 (ref. 4).

In the lower Mach number range the triangular control shows an advantage over the rectangular control. Configuration 1 shows some negative torque at low Mach numbers. It was observed that the trend of servo torque with Mach number for this configuration could be attributed to the properties of the wing alone rather than to interference between wing and body. As a result the trend could be made flatter if the thickness distribution of the wing were properly chosen, say possibly a conical thickness distribution. For configuration 2 the servo torque is large and positive at the lower Mach numbers. This trend with Mach number can be traced to the well-known result that the center of pressure of a rectangular wing tends to move toward the leading edge as the Mach number tends to unity. For the example the center of pressure of the wing alone moved forward 8 percent of the chord between Mach numbers of 2 and 1.5. Configuration 3 shows a relatively flat torque curve at the higher Mach numbers. It has been included to show that above a Mach number of 2 rectangular controls do not necessarily develop large torques. Also shown in the figure are two solid points from figure 3 showing the servo torques under high-altitude, high-normal-acceleration conditions for configurations 1 and 2. Figure 4 shows that the altitude effect on servo torque for configuration 1 at $M = 3.36$ is of the same order of magnitude as the Mach number effect for configuration 2 between Mach numbers of 1.5 and 2.0. It appears that below a Mach number of 2 triangular controls should have lower servo torque than rectangular controls, but that above 2 rectangular controls should have lower torque, at least for extreme performance. Other plan forms may have better characteristics than either triangular or rectangular plan forms. The use of spoilers to reduce the hinge moments of rectangular controls in the lower supersonic range will subsequently be described.

Effect of Wing on Body Loading

There are certain nonlinearities noted in the control-surface effectiveness associated with transference of load from wing to body which have bearing on maneuverability and trim. For instance at high control deflections much of the load that might be developed by the body because of control deflection is lost. This effect is illustrated in

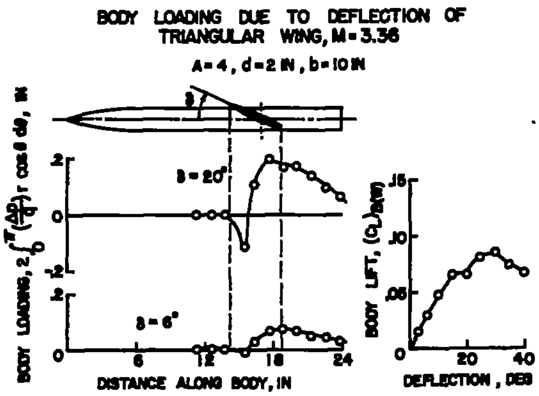

Figure 5

figure 5 which is for a triangular all-movable control of aspect ratio 4. For a control deflection of 6° the body loading is uniformly positive in the conventional manner, but for a deflection of 20° negative local body loading is developed. This loss of lift can be ascribed to a bleeding of the positive pressures on the bottom of the wing onto the top of the body. The lift on the wing in the presence of the body does not increase significantly beyond a deflection of 20° as a result of this effect. For a control of longer chord it was found that the lift transferred to the body falls to negative values as a result of unporting of the control. As a result of the shape of the load distribution, large nose-down pitching moments are developed. It thus appears that the use of short-chord controls is advantageous from the standpoints of both maneuverability and trim. Also in the case of cruciform configurations shorter chords permit higher deflections without physical interference between adjacent panels.

CONTROLS FOR REDUCING HINGE MOMENTS

In the first part of the paper we have considered the use of all-movable controls, particularly as far as extreme performance is concerned, and found that large hinge moments can occur. The second part of the paper is devoted to schemes for reducing or eliminating hinge moments.

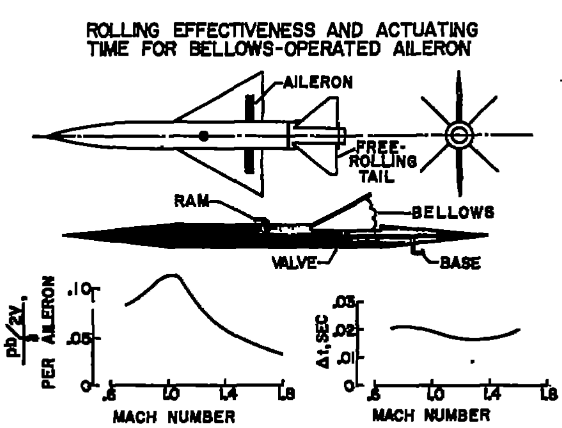

Figure 6

Bellows-Actuated Ailerons

An arrangement (ref. 5) in which ram air is utilized to overcome aileron hinge moments is shown in figure 6. Each side of the wing possesses an aileron actuated by a bellows energized either by ram pressure or base pressure through a fast-acting valve. This arrangement has been flight-tested up to Mach numbers of 1.8 by PARD. The partial-span split-flap ailerons were tested on a missile having a 60° swept wing with a free-rolling tail. Maximum control deflections of the order of 20° were obtained. Although the rolling effectiveness parameter was high at subsonic speeds, it dropped to about one third of its maximum value at a Mach number of 1.8, even though 20° of control deflection were maintained. To actuate the control required only two hundredths of a second. In this time the missile traveled 15 to 30 mean aerodynamic chord lengths (M.A.C. = 14 inches). It appears that this type of control has applications for roll control where large induced rolling moments are not developed.

Automatic Spoiler

Up to this time many data have been issued by the NACA on spoilers, and such data have been summarized by Lowry (ref. 6). A particular use for some of these data (ref. 7) would be the design of a spoiler for reducing the high hinge moments developed by rectangular all-movable wings in the lower supersonic range. In figure 7 is shown the spoiler height necessary to trim an all-movable rectangular control at a Mach number of 1.96. The hinge line of the all-movable control has been placed so that the hinge moments are nearly zero at a Mach number of 1.4. The height of the trailing-edge spoiler necessary to trim the hinge moment when the Mach number is changed to 1.96 is shown in the upper curve. A height slightly more than 2 percent of the chord will be sufficient up to control deflections of 16°. The wing moments that must be overcome by the spoiler are shown in the lower part of the figure.

SPOILER HEIGHT FOR TRIMMING ALL-MOVABLE WING, M=1.96

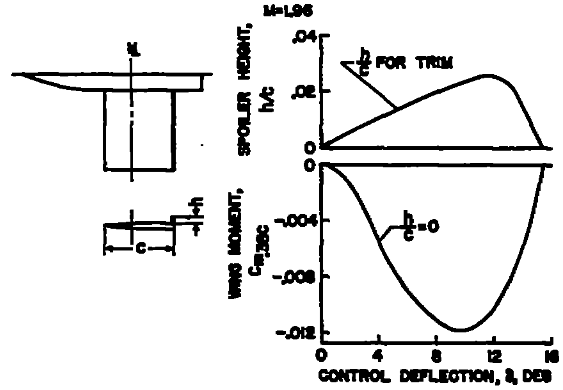

Figure 7

An idea for a spoiler that will automatically trim an all-movable wing has been advanced at the Ames Laboratory. This device shown in figure 8 consists essentially of a mechanically linked, trailing-edge spoiler which actuates and stabilizes the control. The wing is mounted on its hinge axis free to rotate, and its equilibrium position for a fixed crank position is controlled by the induced pressure field of the spoiler.

CONTROL ACTUATED BY SERVO SPOILER, NO DAMPING

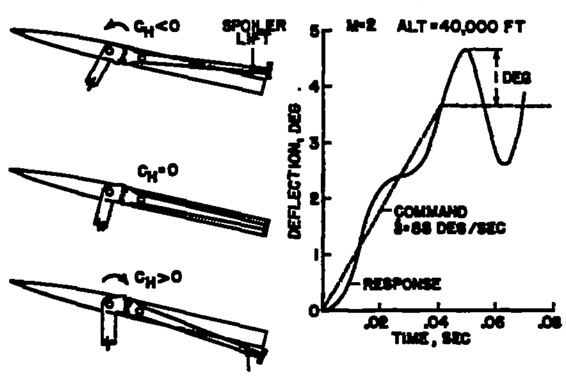

Figure 8

The equilibrium attitude of the wing is determined by the crank position. If for a fixed crank position a nose-down tendency exists, as shown in the upper sketch, the control moves to a lower attitude than its equilibrium attitude. The gearing is such that the spoiler then moves up faster than the trailing edge. The spoiler thus induces a download which tends to return the control to the equilibrium position. Likewise, if the hinge moment is positive or nose-up, the spoiler moves down faster than the trailing edge and returns the wing to an equilibrium trim position as shown by the action in the lower sketch. The spoiler is positioned by the error between the actual control position and the equilibrium trim position corresponding to the crank position. It always acts to minimize this difference and stabilize the control irrespective of the sign of C_{H_δ}.

To show the response characteristics with this servo spoiler, the curves shown on the right side of figure 8 have been prepared. The response of the wing to a command signal of 88° per second for about 0.04 second has been computed assuming no viscous damping. Also instantaneous response of the spoiler was assumed, a reasonable assumption in the light of the estimated response time of 1 millisecond. The spoiler overrides the control, alternately accelerating and decelerating it. The command rate was so chosen to obtain an overshoot of 1° with no damping. With damping the overshoot will, of course, be reduced and the input rate can then be increased.

Air-Jet Spoilers

An interesting idea for eliminating hinge moments altogether is the use of air-jet spoilers. At the Langley Laboratory the use of air-jet spoilers as a missile control has been investigated at transonic speeds in the 7- by 10-foot wind tunnel and at Mach numbers up to 1.6 by PARD. Some rocket-firing results on rolling effectiveness are presented in figure 9. In this figure air-jet spoilers are compared with an all-movable control, plain aileron, and split flap. The air is taken in through round inlets on the tip of the panels and expelled through orifices near the wing trailing edges in a direction 20° forward of the normal to the surface. The rolling effectiveness of the spoilers at subsonic speeds compares favorably with that for the plain aileron deflected 3°.

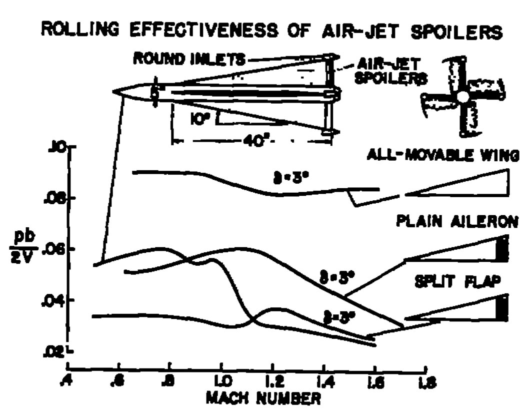

Figure 9

At supersonic speeds the air-jet effectiveness decreases to about one-half that of the plain aileron. It thus appears that air-jet spoilers can be used to simplify roll control for configurations such as the present one which do not develop large induced rolling moments. The characteristics of air-jet spoilers at high angles of attack and high Mach numbers remain to be investigated.

CONCLUDING REMARKS

In the first part of the paper it was shown how all-movable wings retain their lift effectiveness up to a combined angle of the angles of attack and wing deflection of about 45°. The nonlinearities in the hinge moments of rectangular and triangular all-movable wings were pointed out. In the second part of the paper schemes for reducing or eliminating hinge moments were discussed.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Apr. 12, 1955

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